The Pebble-Bed AHTR Liquid Salt Cooled Reactor

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Forum on Small and Medium Reactors (SMRs): Benefits and Challenges
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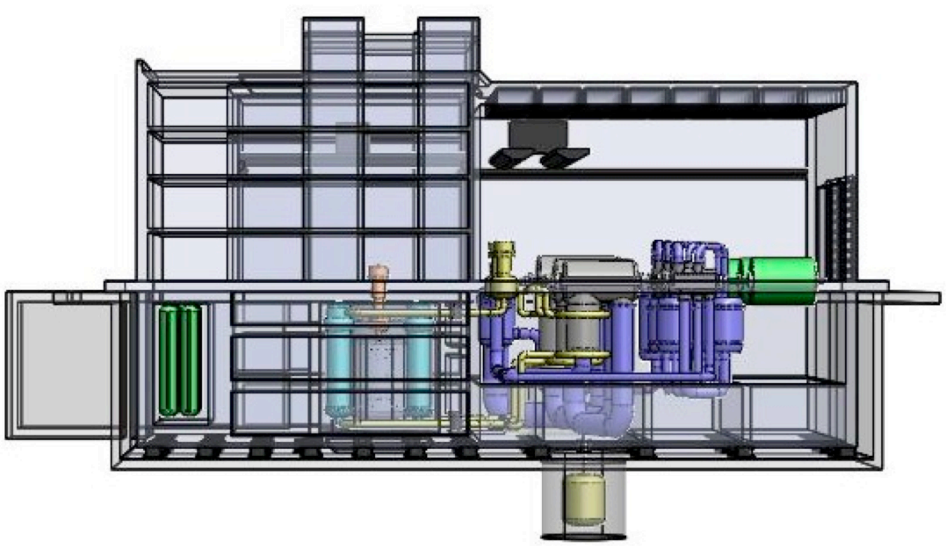
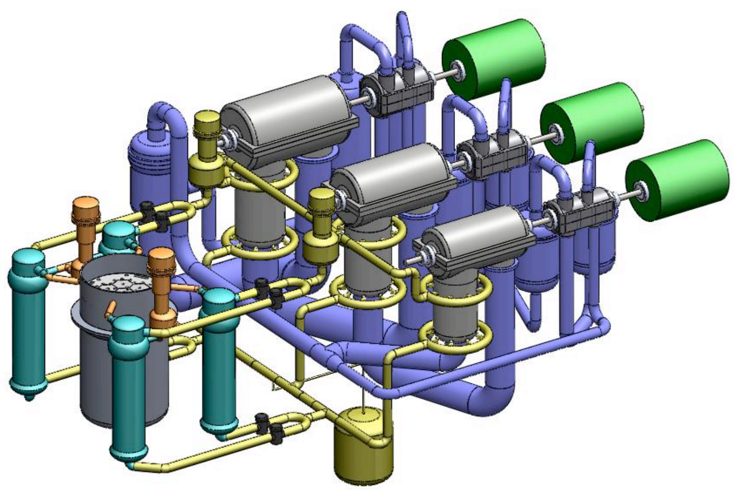
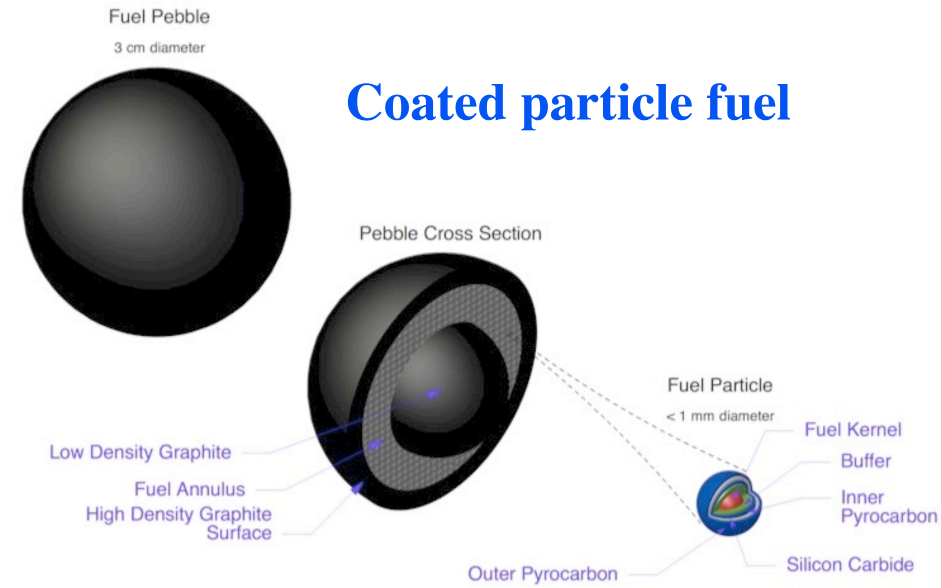


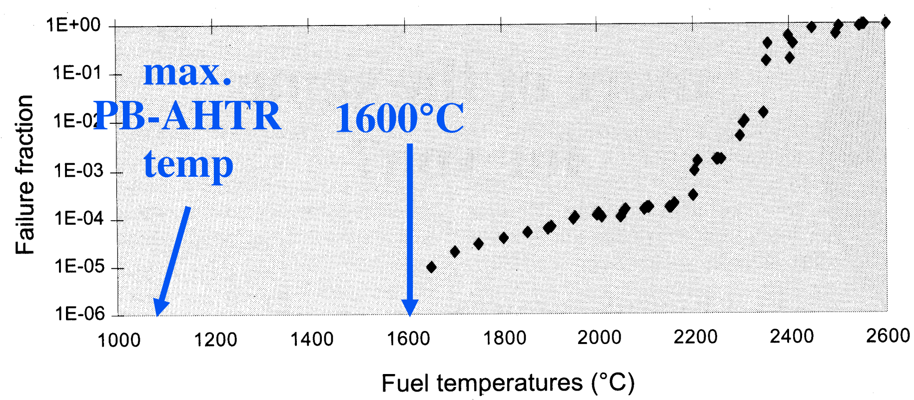


900 MWth, 410 MWe PB-AHTR

Advanced High Temperature Reactors (AHTRs) combine two older technologies

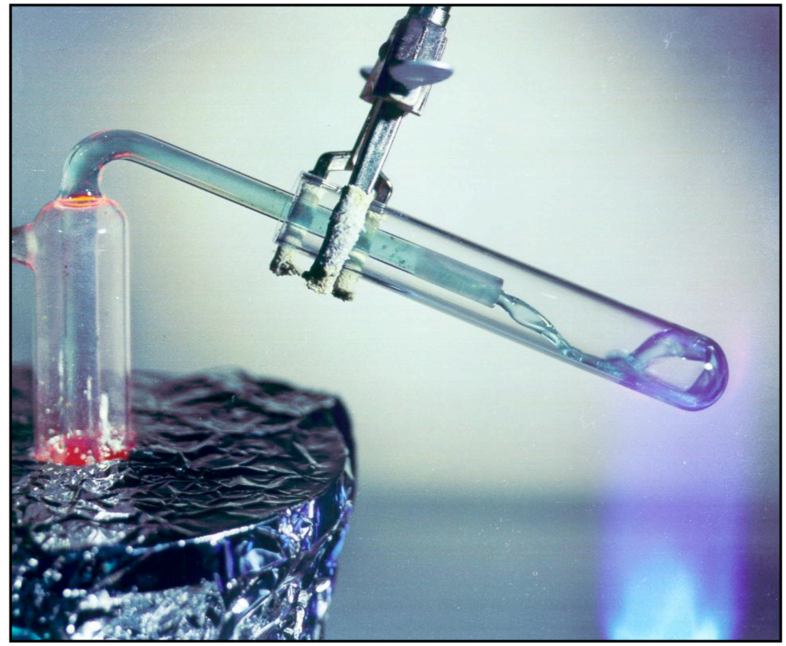
Coated particle fuel





Fuel performance chart (Source: PBMR [Pty] Ltd.)

AHTRs have <u>uniquely</u> large fuel thermal margin



Liquid fluoride salt coolants

Excellent heat transfer
Transparent, clean fluoride salt
Boiling point ~1400°C
Reacts very slowly in air
No energy source to pressurize containment
<u>But</u> high freezing temperature (459°C)
<u>And</u> industrial safety required for Be

Liquid fluoride salts have fundamentally <u>different</u> properties than other reactor coolants

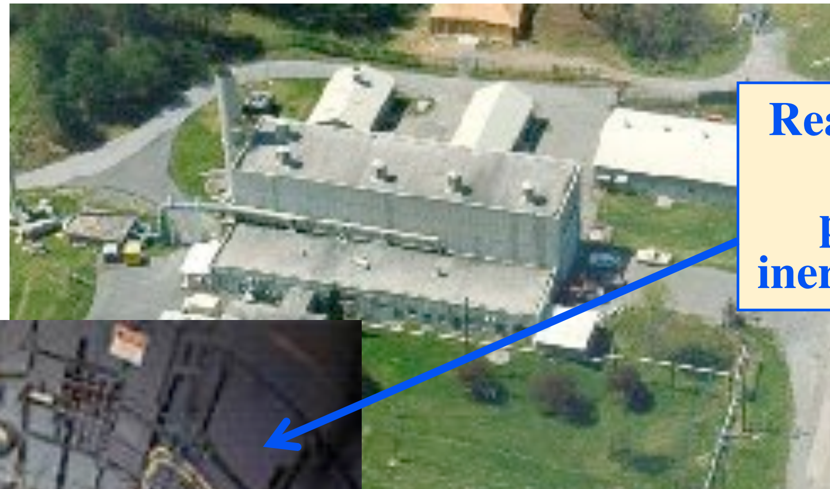
Thermophysical Properties* of S-PRISM, GT-MHR, and AHTR Reactor Coolants and Materials

Material	T_{melt} (°C)	T_{boil} (°C)	ρ (kg/m^3)	C_p (kJ/kg°C)	ρC_p (kJ/m^3°C)	k (W/m°C)	$\nu \cdot 10^6$ (m^2/s)
$^7Li_2BeF_4$ (Flibe)	459	1430	1940	2.34	4540	1.0	2.9
0.58NaF-0.42ZrF$_4$	500	1290	3140	1.17	3670	~1	0.53
Sodium	97.8	883	790	1.27	1000	62	0.25
Lead	328	1750	10 540	0.16	1700	16	0.13
Helium (7.5 MPa)			3.8	5.2	20	0.29	11.0
Water (7.5 MPa)	0	100	732	5.5	4040	0.56	0.13
Hastalloy C-276	~1350		8890	0.43	3820	9.8	
Graphite			1700	1.90	3230	200	

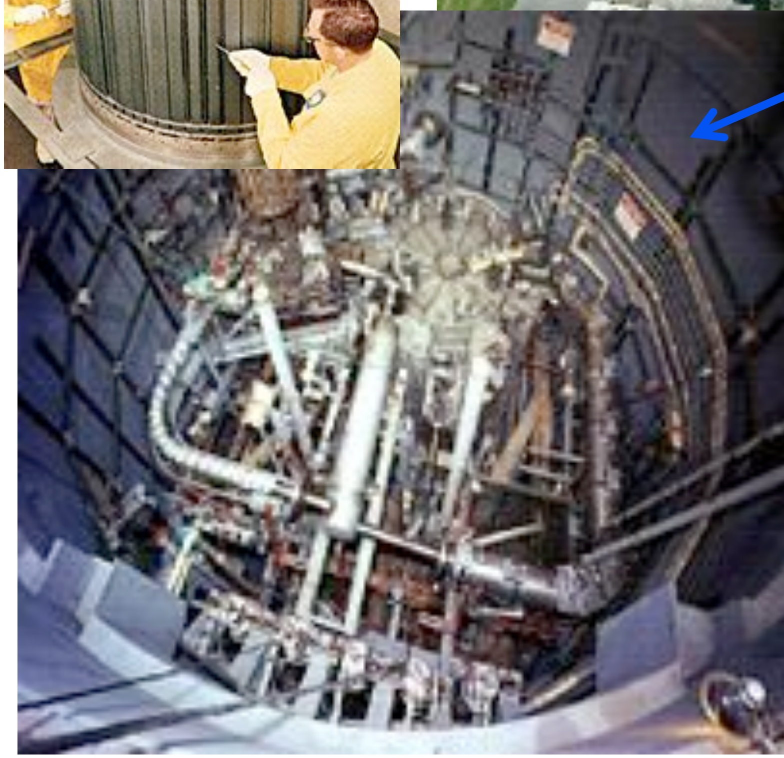
*Approximate physical properties 700°C except the pressurized water data shown at 290°C for comparison; ρ = density, C_p = specific heat, k = thermal conductivity, ν = viscosity.

- **High volumetric heat capacity provides high thermal inertia**
  - **High power density, low pressure operation possible compared to helium cooled reactors**
  - **High efficiency, compact primary loop equipment compared to water cooled reactors**
  - **Transparent coolant, low thermal shock, low chemical reactivity, compact primary loop equipment compared to sodium cooled reactors**
  - **But high freezing temperature still requires safety systems to prevent and control slowly evolving overcooling transients**

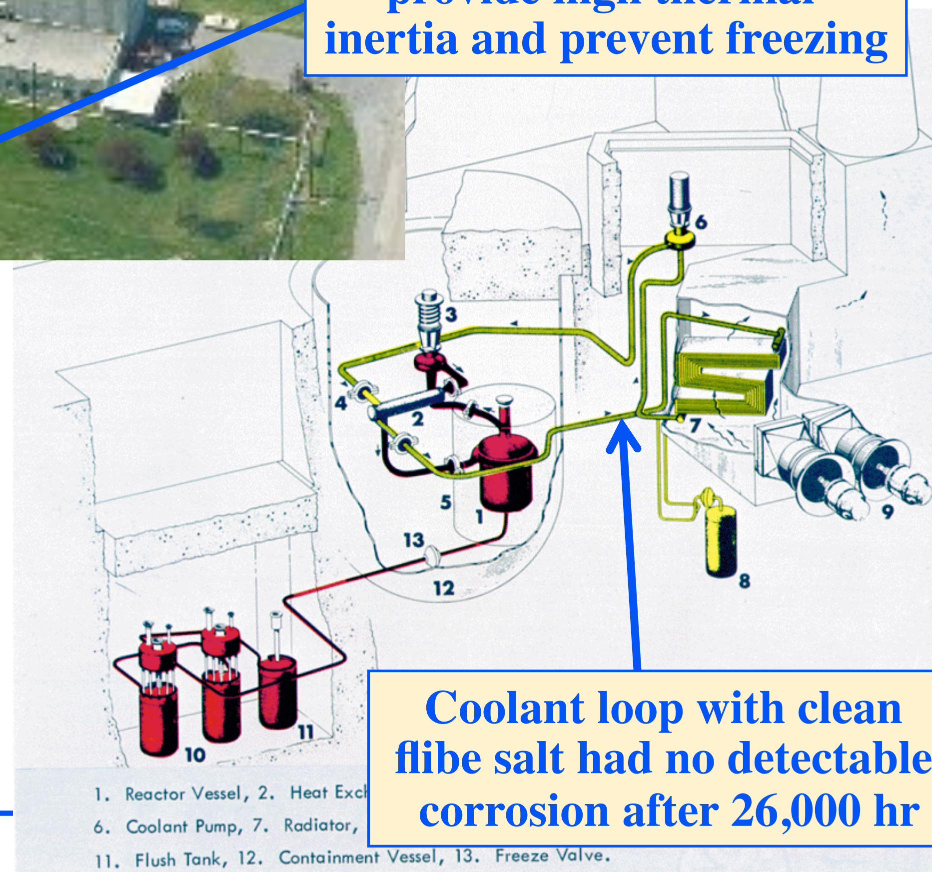
The 8-MWth MSRE (1965-69) provided experience relevant to the development of an AHTR Test Reactor



Reactor cavity acted as an insulated furnace to provide high thermal inertia and prevent freezing

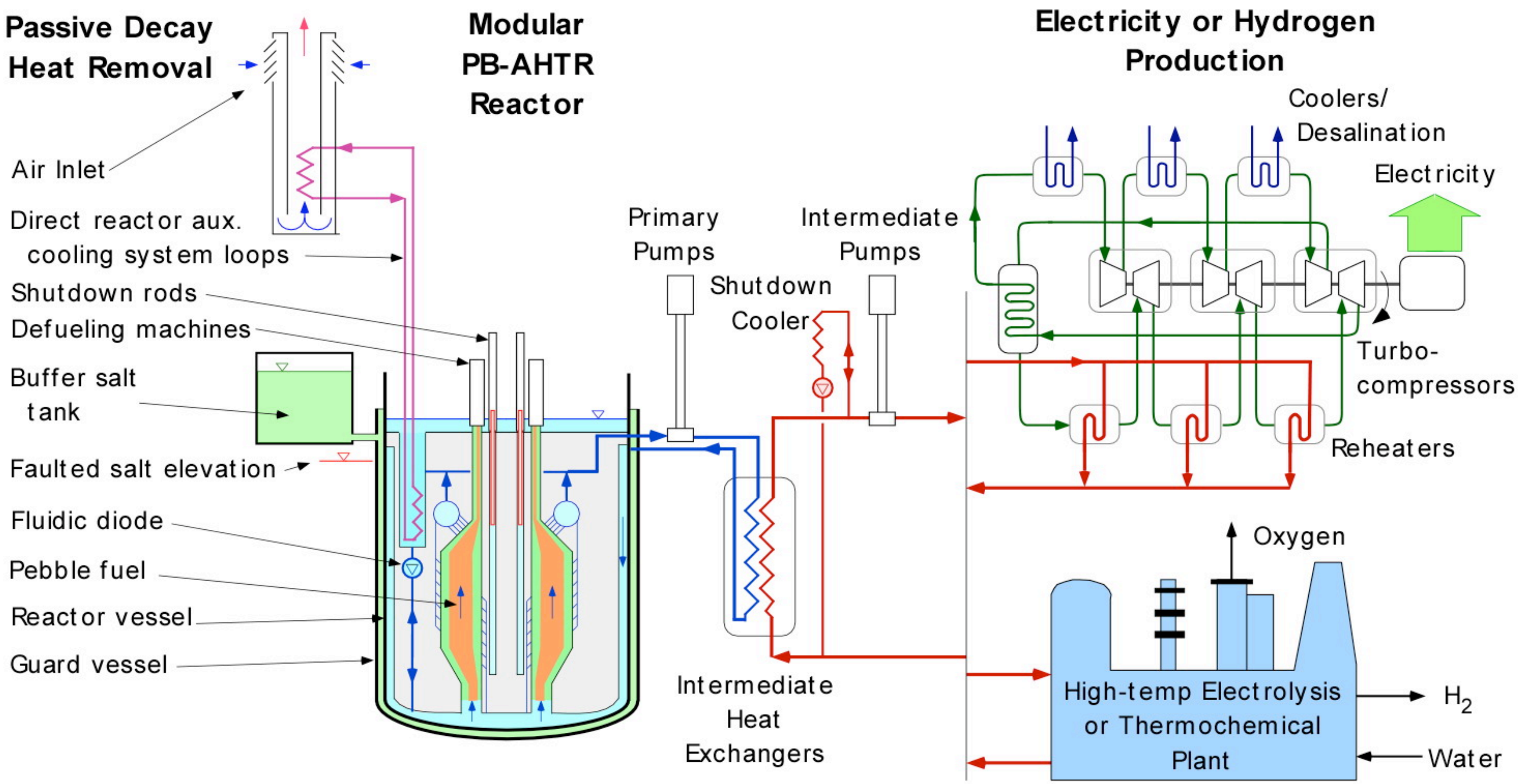


MSRE Systems and Components Performance, Oak Ridge National Laboratory, ORNL-TM- 3039, June 1973.



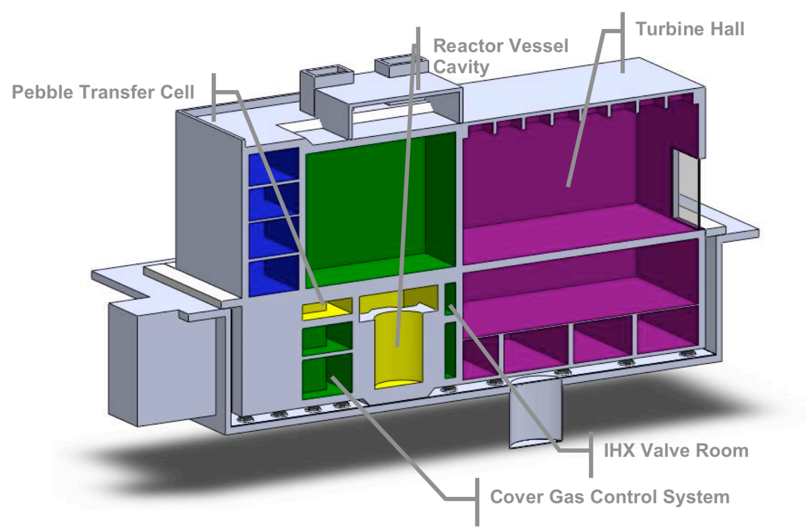
Coolant loop with clean flibe salt had no detectable corrosion after 26,000 hr

The modular PB-AHTR is a compact pool-type reactor with passive decay heat removal

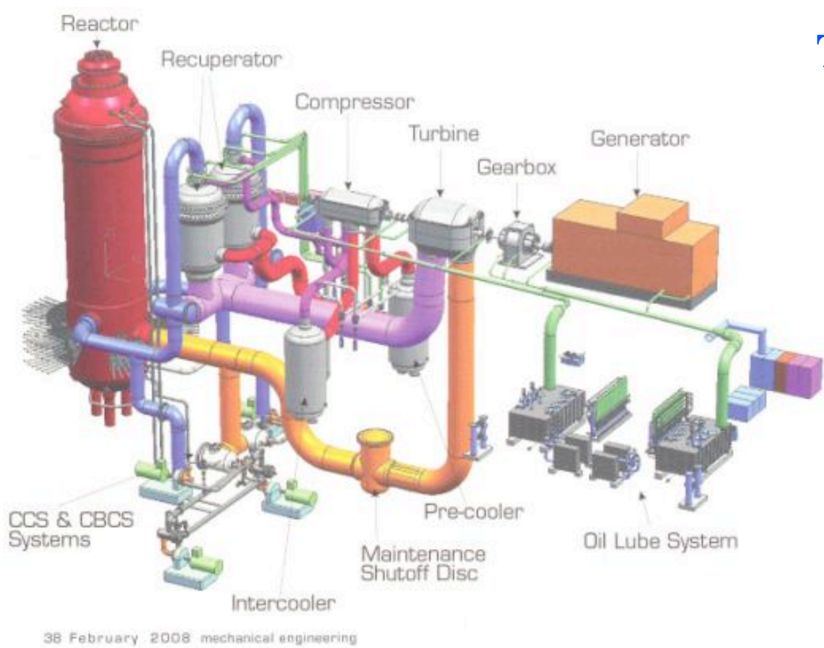


AHTRs have a uniquely large number of robust safety barriers

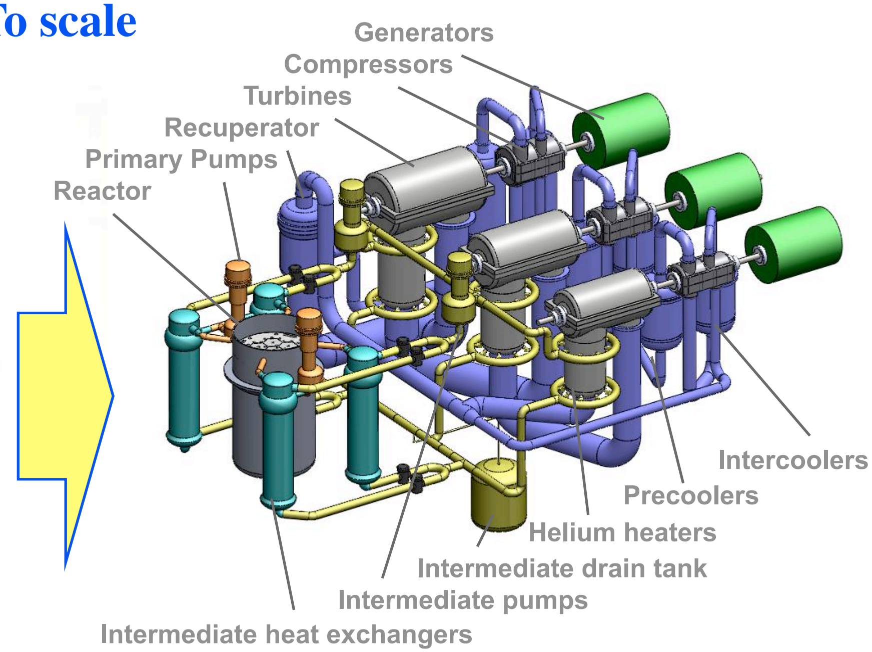
- **Ceramic TRISO fuel**
  - **Over 500°C temperature margin to fuel failure under transients and accidents**
  - **Immersion in chemically inert coolant with high fission product sorption capacity makes air/steam ingress impossible**
  - **Negative coolant void/temperature reactivity feedback**
  - **Passive natural-circulation decay heat removal**
- **Reactor cavity acts as a low-pressure, low leakage containment**
  - **No stored energy sources to pressurize containment**
  - **Large thermal inertia of cavity provides long time constant to primary coolant freezing**
- **Reactor citadel acts as a filtered confinement**
- **External event shell and turbine hall provide additional hold up**



The PB-AHTR power conversion system design is derived from the PBMR/Mitsubishi design



To scale



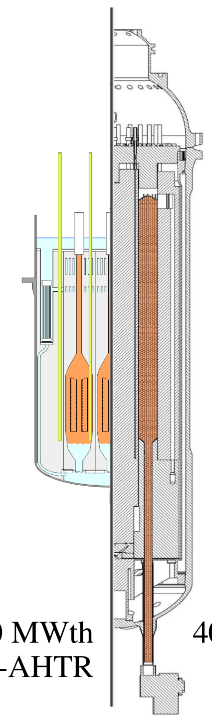
168-MWe PBMR/Mitsubishi helium cooled HTR

410-MWe PB-AHTR liquid cooled HTR

Trade study needed for multi-reheat helium Brayton vs. combined cycle vs. supercritical-CO_2

Modular PB-AHTR Economics

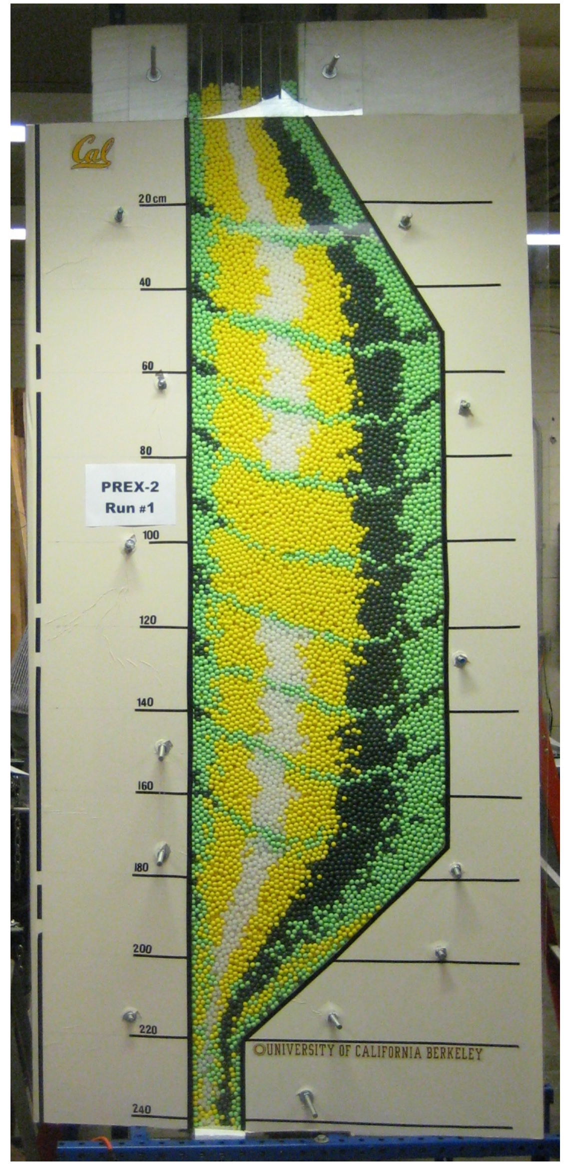
- **Lower energy costs than ALWRs**
  - Primary loop components more compact than ALWRs (per MWth)
  - No stored energy source requiring a large-dry or pressure-suppression-type containment; reactor building volume 50% smaller than ABWR (per MWe)
  - Gas-Brayton power conversion 40% more efficient, turbine building 55% smaller than ABWR (per MWe)
- **Much lower construction cost than SFR/IFR**
  - ORNL top down, apples-to-apples cost study [1] concluded that the AHTR capital cost is 56% of the S-PRISM cost
  - Primary loop is much more compact (salt heat capacity is 4.5 times higher than sodium)
  - Low pressure containment (no sodium reaction)
  - Intrinsically higher temperature/power conversion efficiency
- **Much lower construction cost than MHRs**
  - All components much smaller, operate at low pressure, compared to MHRs



1. D. T. Ingersoll, et al., "Status of Preconceptual Design of the Advanced High-Temperature Reactor (AHTR)," ORNL/TM-2004/104, pp. 69, 2004.

PREX-2 has confirmed radial zoning capability

- **15° sector PREX-2 experiment simulating 900-MWth annular core**
  - **129,840 colored 1.28-cm diameter HDPE pebbles in 15° sector**
  - **Average of 9460 + 1260 pebbles in each axial layer**
- **For simplicity PREX-2 is a dry experiment (unlike PREX-1), so pebbles are added to the top of the core and removed from the bottom**
  - **Hydrodynamic forces on pebbles neglected; must be studied later**



PREX-2 Run#1

The current Modular PB-AHTR plant design is compact compared to LWRs and MHRs

Reactor Type	Reactor Power (MWe)	Reactor and Auxiliaries Volume (m^3/MWe)	Turbine Building Volume (m^3/MWe)	Ancillary Structures Volume (m^3/MWe)	Total Building Volume (m^3/MWe)
1970’s PWR	1000	129	161	46	336
ABWR	1380	211	252	23	486
ESBWR	1550†	132†	166	45	343
EPR	1600	228	107	87	422
GT-MHR	286	388	0	24	412
PBMR	170	1015	0	270	1285
Modular PB-AHTR	410	105	115	40	**260**

† The ESBWR power and reactor building volume are updated values based on the Design Certification application arrangement drawings.

The current UCB thermal hydraulics test program has 3 facilities

PREX
Pebble recirculation IET
Match Re, Fr, pebble/salt density ratio w/ water

S-HT^2
Salt heat transfer SET
Match Re, Fr, Pr, Gr w/ Dowtherm A

PRISM
Passive shutdown rod IET
Match Re, Fr, rod/salt density ratio w/ sugar water

Dowtherm heat transfer oil will be used as the principal simulant fluid for AHTR IET/SET experiments

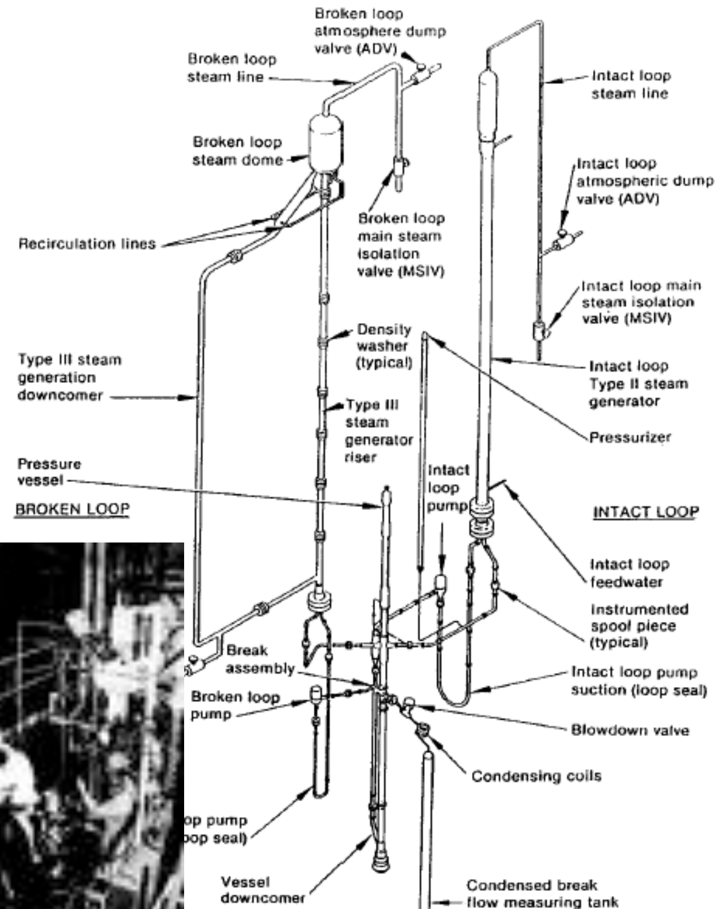
Scaling parameters to match Pr, Re, Gr, and Fr for flibe and Dowtherm A

Flibe Temperature [$^\circ C$]		600	650	700	750	800	850
Dowtherm A Temperature [$^\circ C$]		63	82	104	129	157	191
Length scale	l_m/l	0.52	0.51	0.49	0.46	0.44	0.41
Velocity scale	u_m/u	0.72	0.72	0.70	0.68	0.66	0.64
ΔT scale	$\Delta T_m/\Delta T$	0.30	0.30	0.30	0.30	0.29	0.29
Heat conductivity	λ_m/λ	0.14	0.13	0.13	0.12	0.12	0.11
Ther. diffusivity	α_m/α	0.37	0.35	0.33	0.31	0.28	0.26
$\beta\Delta T$	$(\beta\Delta T)_m/\beta\Delta T$	1.00	1.00	1.00	1.00	1.00	1.00
$\gamma\Delta T$	$(\gamma\Delta T)_m/\gamma\Delta T$	0.81	0.94	1.06	1.13	1.13	1.04
$\kappa\Delta T$	$(\kappa\Delta T)_m/\kappa\Delta T$	-0.84	-0.86	-0.89	-0.92	-0.95	-0.99
Pumping power	$P_{p,m}/P_p$	5.2%	5.0%	4.2%	3.4%	2.8%	2.1%
Heating power	$P_{q,m}/P_q$	2.1%	2.1%	1.9%	1.7%	1.5%	1.3%

- Note that Pr, Re, Gr and Fr can be matched at < 2% of prototypical heater power
- Water can be used for hydrodynamics experiments

The new UCB Compact Integral Effects Test (CIET) facility can be compared to the INL Semiscale facility

- **Semiscale simulation of PWR LOCA**
  - **1:1 height**
  - **1:1705 flow area**
  - **1:1705 power (2 MW)**
  - **1:1 time**
  - **prototype temperature / pressure**
- **CIET simulation of the PB-AHTR LOFC/ ATWS**
  - **1:1 effective height (1:2 actual)**
  - **1:190 effective flow area (1:756 actual)**
  - **1:190 effective power (1:9000 actual, 100 kW)**
  - **1:(2)$^{1/2}$ time**
  - **reduced temperature / pressure**
  - **reduced heat loss**
  - **small distortion from thermal radiation**



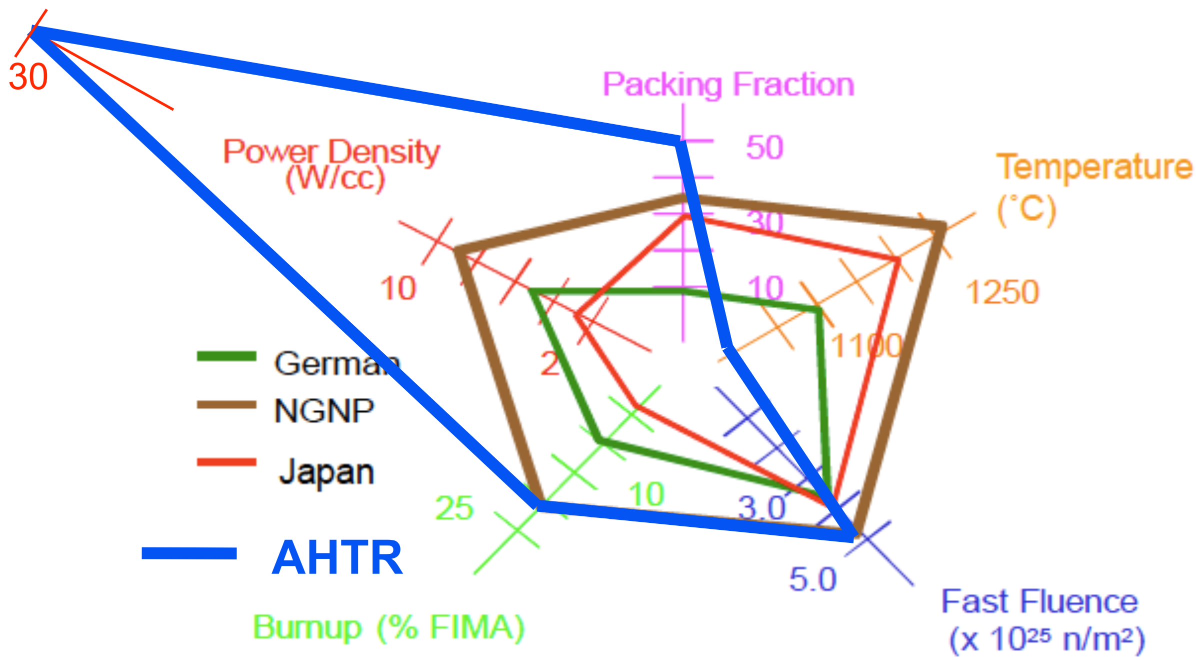
e 2.2.1 Semiscale Mod-2C. (From Ref. 2.2.2.)

Semiscale, INL

See http://users.owt.com/smsrpm/nksafe/testfac.html for a list of other LWR IET's

PB-AHTR fuel development can use existing NGNP fuel fabrication and qualification infrastructure

- **PB-AHTR fuel operates at high power density and heavy metal loading, but lower temperature, than NGNP fuel**
- **Rapid fuel testing is possible due to short time required for LEU and LWR-TRU fuel to reach full discharge burn up**



Conclusions

- **Fluoride-salt cooled reactors have unique safety, efficiency, and economic potential**
- **AHTR development involves a number of different experimental programs**
  - **Integral effects tests**
    - » **CIET validation transient thermal hydraulics models**
    - » **PREX validation pebble recirculation models**
    - » **ATR/HFIR fuel performance**
  - **Separate effects tests**
    - » **Many with simulant/prototypical fluids**
  - **Component tests**
    - » **Functional tests w/ water, CTF tests w/ salt)**
  - **Test reactor tests**
    - » **MSRE-size test reactor facility**